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Cross-modal enhancement of perceived brightness: Sensory interaction versus response bias

Yoav Arieh
Montclair State University, ariehy@montclair.edu

Lawrence E. Marks
Yale University, lawrence.marks@yale.edu

Eric C. Odgaard
University of Tampa, eodgaard@ut.edu

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Cross-modal enhancement of perceived brightness: Sensory interaction versus response bias

ERIC C. ODGAARD, YOAV ARIEH, and LAWRENCE E. MARKS
John B. Pierce Laboratory, New Haven, Connecticut
and Yale University School of Medicine, New Haven, Connecticut

Stein, London, Wilkinson, and Price (1996) reported the presence of cross-modal enhancement of perceived visual intensity: Participants tended to rate weak lights as brighter when accompanied by a concurrent pulse of white noise than when presented alone. In the present study, two methods were used to determine whether the enhancement reflects an early-stage sensory process or a later-stage decisional process, such as a response bias. First, enhancement was eliminated when the noise accompanied the light on only 25% versus 50% of the trials. Second, enhancement was absent when tested with a paired-comparison method. These findings are consistent with the hypothesis that the sound-induced enhancement in judgments of brightness reflects a response bias, rather than an early sensory process—that is, enhancement is the result of a relatively late decisional process.

In recent years, there has been growing recognition that inputs from different sensory modalities are not always, or perhaps even typically, processed in isolation from one another but may interact in a variety of ways (see Buchtel & Butter, 1988; Nickerson, 1973; Seif & Howard, 1975; Spence & Driver, 1997; Vroomen & de Gelder, 2000; Ward, 1994). Mounting evidence has revealed interactions between effects of visual and auditory stimuli, notably in the spatial domain, where displacing the location of a visual stimulus commonly (although not always) influences the perceived location of a simultaneously presented auditory stimulus—the so-called *ventriloquist effect* (Bertelson, Vroomen, de Gelder, & Driver, 2000; Choe, Welch, Gilford, & Juola, 1975). Far less clear is the existence of such interactions within the intensive domain. Despite a long history of research into the question of whether, for example, an auditory stimulus is better detected when a visual stimulus is presented simultaneously, or vice versa, few clear conclusions are possible, many of the older studies having failed to control for possible variations in response criterion (see Bernstein, Clark, & Edelstein, 1969; Hershenson, 1962; Taylor & Campbell, 1976). Use of criterion-controlled methods and analyses in terms of signal detection theory have provided little evidence of cross-modal interactions at a sensory level (Bothe & Marks, 1970; Kuze, 1995; Taylor & Campbell, 1976).

Given this history, the report by Stein, London, Wilkinson, and Price (1996) has considerable potential import. Stein et al. reported that observers rated weak flashes of light to be brighter when accompanied with concurrent pulses of 45-dB white noise than when the pulses of noise were withheld. Of special interest are the spatial conditions that yielded evidence of cross-modal enhancement—and those that did not. In their first experiment, Stein et al. placed both the source of the visual stimulus (a light-emitting diode, or LED) and the loudspeaker directly in front of the observer, a condition that produced enhancement. In a second experiment, Stein et al. again placed the LED directly in front of the observer but now varied the location of the auditory stimulus randomly, from trial to trial, to the left and right of the LED—a condition that also induced enhancement in the brightness ratings. Finally, Stein et al. varied the spatial locations of both the visual target and the irrelevant auditory stimulus to the left or right of fixation from trial to trial, and in this case enhancement was absent. To summarize these results: Cross-modal enhancement of rated brightness seems to depend on the location of the visual stimulus within the visual field, but not on the location of the auditory stimulus.

Stein et al. (1996) recognized that this pattern of outcomes is not readily compatible with neurophysiological findings on visual–auditory interaction—for instance, cells in the midbrain that are multimodally responsive typically require spatial coregistration (see, e.g., Stein & Meredith, 1993). Nevertheless, Stein et al. concluded that the cross-modal interactions they observed in ratings of brightness reflected a true sensory enhancement—an increase in the brightness of near-threshold lights, possibly reflecting a contribution of multimodally responsive neurons in the brain stem.

As others (e.g., Vroomen & de Gelder, 2000) have noted, however, the results of Stein et al. (1996) do not speak ex-

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plicitly to the following question: Does the auditory–visual interaction take place at an early, sensory stage or at a later, decisional stage of processing? That is, the experiments of Stein et al. did not distinguish between two possible explanations: sensory enhancement and response bias. Our suspicion that the effects reported by Stein et al. were more likely based in decisional processes than in sensory processes led us to extend Stein et al.'s paradigm in two ways that might help illuminate the source of these effects. First, we varied the proportion of trials on which a sound accompanied the visual stimulus; research on the detectability of weak signals has shown that presentation probabilities can modify response criterion (Experiment 1). Second, we tested for cross-modal interaction by using a method of paired comparison (Experiment 2), since this method may be less susceptible to response bias than is the rating method used by Stein et al. and by the present investigators in the first experiment of this study.

Within signal detection theory, one of the fundamental demonstrations of response bias is achieved through the manipulation of probabilities of presenting different kinds of stimuli within a session. In fact, manipulating the probabilities with which target stimuli are presented has revealed shifts in criterion not only in simple detection tasks (e.g., Nachmias, 1968), but also in numerous other experimental tasks and conditions, including reaction time (Hansen & Well, 1984), same–different judgment (Thomas, Windell, Williams, & White, 1985), stimulus categorization (LaBerge & Tweedy, 1964), perception of intensity (Chase, Bugnacki, Braida, & Durlach, 1983), and stimulus recognition (Tanner, Haller, & Atkinson, 1967). One theme common to all of these reports is that manipulating the relative frequency or probability of presenting a stimulus or some attribute of the stimulus, such as the loudness of an auditory signal, produces systematic shifts in the observers' response criterion. What is also common to these reports is the interpretation of such criterion shifts as the result of a response bias, rather than of some early sensory process.

The fundamental difference between each of these reports and that of Stein et al. (1996) is that the presence or absence of noise is, at least by instruction, an irrelevant stimulus event in Stein et al.'s design and in the design of the present study, rather than a manipulation of some aspect of the actual target. The logic of the design, however, remains the same. In the present case, if presenting a burst of noise enhances the brightness of a concurrent flash of light through an early sensory process, this enhancement should take place largely independently of the proportion of trials on which sounds accompany the lights. At least, this should be so to the extent that presenting the sound on a smaller or greater proportion of trials has no effect on the early sensory processing, and there seems little or no reason to expect that it would—unless the sounds are presented at levels sufficiently high enough to produce auditory fatigue or other adaptation-like effects. On the other hand, a substantial effect of presentation probability on the cross-modal enhancement would implicate some kind of response bias or criterion shift. In detection tasks such as those mentioned above, for instance, increasing the probability of presenting signal plus noise, rather than noise alone, typically induces participants to shift their response criterion, thereby helping to maintain a high overall level of performance. An analogous process might operate on the enhancement of ratings of intensity, if this, too, is a criterion-dependent phenomenon. In Experiment 1, we therefore varied the proportion of the trials on which an irrelevant sound accompanied the visual target stimulus.

Next, we asked whether the cross-modal interaction depends on the use of a particular psychophysical task, the rating of brightness. If the enhancement has a sensory basis, it should reveal itself in a variety of psychophysical tasks. Single-stimulus designs, such as those used in rating tasks, are notably susceptible to response biases (Green & Swets, 1966; Tanner et al., 1967). The search for methods by which to minimize such biases has yielded a variety of experimental methods, such as *n*-alternative forced choice. To a similar end, in Experiment 2, a paired comparison procedure was used to determine whether the enhancement seen in ratings of brightness would also be evident when participants compared directly, on each trial, the brightness of flashes of lights accompanied and not accompanied by pulses of noise. In this case, a positive result would not be decisive: If the participants judged a light accompanied by noise to be greater in brightness than the same light without noise, the result would be consistent with both sensory and decisional models. But a negative result—elimination of the enhancement in direct comparison—would speak against an explanation in terms of sensory enhancement and in favor of response bias.

EXPERIMENT 1

In the first experiment, we examined the effect of the presentation probability of noise on the cross-modal enhancement of perceived visual intensity. To this end, we began by replicating the cross-modal enhancement reported by Stein et al. (1996), who presented concurrent noise on 50% of the trials. The replication was motivated, in part, by uncertainties regarding the stimulus levels used by Stein et al. In Experiment 1A, therefore, we duplicated their design as closely as possible. Then, in Experiment 1B, using a new group of participants, we both increased the probability of concurrent white noise to 75% and decreased it to 25%.

Method

Participants

A total of 9 participants (2 male, 7 female) served in Experiment 1A (the 50% condition; age in years, $M = 24.45$, $SD = 4.91$). Twelve participants (5 male, 7 female) served in the two sessions of Experiment 1B (75% and 25% conditions; age in years, $M = 25.92$, $SD = 4.68$). All the participants were either undergraduate or graduate students at Yale University. The participants were paid $20 for their participation in each session, which took approximately 90 min to complete.

Materials

Light intensities. The uncertainty in stimuli mentioned above refers to the levels of light intensity. Stein et al. (1996) reported using levels within an order of magnitude of 10^{-5} footcandles. Note, however, that the footcandle is a measure of illuminance, of light falling on a surface, and not a measure of luminance, of the level emitted (as in the case of an LED) or reflected. Furthermore, if it is assumed that the intended unit was the *effective* footcandle, or footlambert, with 40-msec flashes of red light, the luminance levels reported by Stein et al. would lie more than one log unit below absolute threshold (Bassi & Powers, 1986; see also the many studies reviewed by Bartlett, 1965). Fortunately, since Stein et al. indicated that their visual stimuli fell just above absolute threshold (indeed, they noted that the lowest light levels they used were not detected on a substantial proportion of trials), we were able to choose light levels near the limits of absolute detection.

To this end, we began by measuring, in 4 participants who did not serve in the main experiments, absolute detection, using a two-alternative forced-choice (2AFC) adaptive procedure with a three-down one-up rule (lower luminance after three successive correct responses, raise it after one incorrect response) with interleaved ascending and descending tracks, a method that converges on a level detected 79% of the time. We next had each of these participants complete a luminance discrimination experiment in which the task was to identify the brighter of two lights presented on each trial. The previously measured detection threshold served as the standard, and the 2AFC procedure converged on a luminance level that was discriminated from that standard 79% of the time. This procedure provided us with four different intensity levels that were one just noticeable difference above the individual 79% thresholds. We selected the highest value from this group for our lowest stimulus intensity (2×10^{-3} ft-L, or 6.7×10^{-3} candela/m^2). Having established the lowest luminance level to use in the main experiments, we then generated a series of logarithmically spaced stimuli by increasing each successive level by approximately 0.4 log luminance unit. Thus the five luminances were 2×10^{-3}, 5×10^{-3}, 1.3×10^{-2}, 3.2×10^{-2}, and 6.9×10^{-2} fL.

To minimize reflections and nonuniformities of luminance across the surface of the LED at low levels, the LED was mounted in a small cylinder behind a 3.0 density neutral Wratten gelatin filter (no. 96). Luminance was measured with a Model 2000 telephotometer from Gamma Scientific, Inc., using a 1º aperture to view the target from a distance of 18 in. (the distance from eye position above the chinrest to target); thus, the luminance levels provided here represent the aggregate measurement across the entire surface of the LED.

Other materials. Red utility goggles were used for dark adaptation. The experiment was conducted in a sound-attenuating chamber, with a chinrest mounted in place to keep the participant's head positioned 18 in. in front of the LED. An Optimus Pro 7AV loudspeaker was positioned directly behind the LED mounting, through which was presented a pulse of broadband noise, 20 Hz–20 kHz (produced by Tucker Davis Technologies System 3). The level of the noise was set at 45 dB A overall level at the chinrest, measured with a GenRad model 1987 Minical sound-level meter. The duration of both the light and the sound was 40 msec, with 5-msec rise and decay for the noise. Following the method of Stein et al. (1996), the participants rated the brightness of each light by rotating an unmarked dial (340º turn radius), which was attached to a linear potentiometer. The mounting of the dial was mobile enough to be moved into position for either the left or the right hand (the dominant hand for each participant). Stimulus presentation and data collection were automated in a Matlab program, operating on a PC with a 700-MHz Pentium III processor. Instructions signaling the end of each trial and the end of each block of trials were delivered through a second loudspeaker, positioned 3 ft to the right and below the LED mounting.

Procedure

The participants were dark-adapted with the red goggles for a period of 15 min, after which the visual detection threshold was determined (79% correct in 2AFC, by the adaptive procedure described above). Only one of the participants (no. 4, in the 50% condition) gave a threshold greater than 2×10^{-3} fL, the lowest luminance level used in the main experiment; the other participants gave thresholds between 6×10^{-4} and 1×10^{-3} fL. Consequently, for Participant 4, the luminance levels in the main Experiment 1A were adjusted by dropping the lowest value of 2×10^{-3} fL and increasing the highest level to 1.4×10^{-1}. This adjustment did not produce any appreciable difference in the pattern of that participant's data, however, so the aggregated analyses presented in the Results section include those of Participant 4.

Following completion of the threshold measurement, the participants were instructed that they would subsequently be presented with a series of trials in which the LED would flash briefly and that their task was to "rate the intensity of the light by turning the dial clockwise, such that the further you turn the dial, the brighter you judge that light to be." The participants were also encouraged to use at least 70% of the dial in making their judgments. The participants were then told that some of the lights might be accompanied by a brief burst of noise but that they should ignore the noise and just rate the intensity of the light. The participants were also informed that they had 3 sec to rate each light, at which time the computer would record the position of the dial. The computer would then instruct them to "reset the dial" to the maximum counterclockwise position to begin the next trial. The participants were also informed of the end of each trial block by the computer, which would instruct them to "put their goggles back on and exit the booth."

Each trial followed a sequence of 2-sec delay, 40-msec stimulus presentation, 3-sec response interval, instructions to reset the dial, and an intertrial delay of variable length, during which the dial was reset to zero (maximum counterclockwise position).

This same general procedure was used in both Experiments 1A and 1B, which differed only in the probability that the burst of noise would accompany the flash of light. The participants were provided with a short block of practice trials (12 in the 50% condition, 11 in the 75% and 25% conditions), during which each of the five light intensities was presented at least once, with the frequency of concurrent noise appropriate to the particular condition. The practice block was followed by feedback informing the participants regarding the amount of the dial used and with a reminder to ignore the noise when rating the intensity of the light flashes. The participants then returned to the booth for three consecutive blocks of trials (110 each in the 50% condition, 100 each in the 75% and 25% conditions), with 5-min breaks scheduled between each block. The data from the practice blocks were discarded from the analyses.

The 50% condition consisted of 330 experimental trials (five different light intensities, with and without noise, presented in random order 11 times in each block). In order to balance the presentation probabilities in the 75% and 25% conditions, the total number of trials was reduced to 300 (five different light intensities presented 20 times in each block, either 15 times with noise and 5 without [75%] or 5 times with noise and 15 without [25%]). The participants in the 50% condition (Experiment 1A) completed all the trials in a single session; the participants in the 75% and 25% conditions (Experiment 1B) served in two separate sessions, counterbalanced in order.

Data Treatment

The linear potentiometer recorded ratings ranging from 0 to 10. Analyses of the raw ratings of the individual participants revealed the following two findings: Some, but not all, of the ratings within individual blocks were skewed beyond $|.80|$, and very different ranges (based on means and standard deviations) were used on individual trial blocks, even within participants. The data in blocks with skewed distributions were corrected either by computing the square root of each value for those blocks with positive skewness (approximately 25% of all blocks) or by squaring the ratings scores for those blocks with negative skewness (approximately 5% of all blocks). All of these corrections brought the skewness value of the relevant data below $|.80|$. Ratings from each block were then transformed to *z* scores

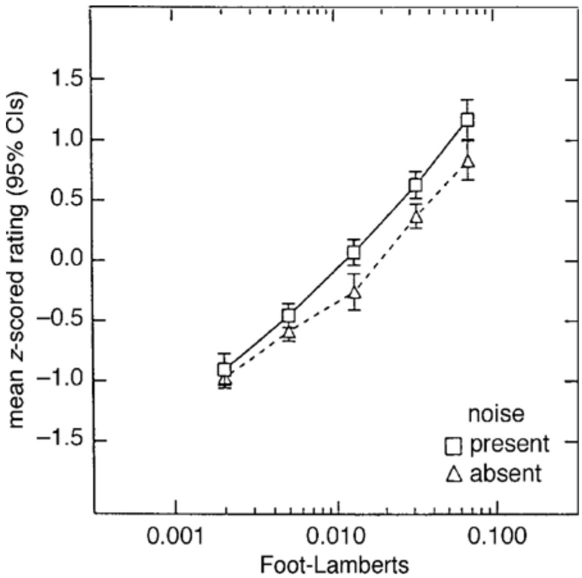

Figure 1. Mean z-scored ratings at each level of light intensity, with and without concurrent noise, for the 50% presentation probability of noise.

in order to remove the biasing effects of mean differences on general linear model analyses.

Results

Experiment 1A: 50% condition

Figure 1 presents the mean of the z-transformed ratings at each luminance level, with and without concurrent noise. A repeated measures factorial analysis of variance (ANOVA) (noise present/absent × 5 light intensity levels) confirms the impression given by the visual inspection of the figure. Mean ratings of perceived intensity were higher, on average, for trials in which noise was present (M = .10) than for trials without noise (M = −.12; $F(1,8) = 28.57$, $p <$ .01]. And although there was a main effect for light intensity [$F(4,5) = 65.62$, $p < .01$], there was no reliable interaction between the presence/absence of noise and light intensity [$F(4,5) = 3.53$, $p = .10$]. These results confirm the initial finding of cross-modal enhancement of perceived visual intensity reported in Stein et al. (1996).

In addition to determining whether cross-modal enhancement was present, we also wanted to estimate the size of the effect of noise. Effect size estimates from the ANOVA just presented are not likely to be accurate, given the considerable variability in the data removed by using only mean intensity ratings. Therefore, for each participant, we performed point-biserial correlations between the rating given on each trial and the binary variable noise present/absent, controlling for the effect of light intensity. The obtained values are presented in Table 1.

As Table 1 indicates, there was a reliable cross-modal enhancement of perceived visual intensity for 8 of the 9 participants. Furthermore, we can aggregate these effect sizes by using meta-analytic techniques for correlations: Fisher's z transform to normalize the correlations, computation of a mean weighted by sample sizes (equal in this case), calculation of confidence intervals, and an inverse Fisher's z transform to return the values to correlations. Employing this technique for the observed effect sizes in Table 1 produces a 95% confidence interval for the correlation effect size of .12 to .19 (z = 8.30).

Experiment 1B: 75% and 25% Conditions

Figure 2 presents the aggregated z-transformed rating at each luminance level, with and without concurrent noise. As the figure makes clear, presenting noise on 75% of the trials led to an increase in ratings of brightness, much as did presenting noise on 50% of the trials (Experiment 1A). Presenting noise on 25% of the trials, however, had no apparent effect on the ratings.

Statistical analyses confirmed these observations. Repeated measures ANOVAs were performed in both conditions, as in Experiment 1A. In the 75% noise condition, the participants tended to rate lights as brighter, on average, when presented with concurrent noise (M = .04) than when presented without [M = −.10; $F(1,11) = 8.96$, $p = .01$]. And, as was the case in the 50% condition, there was a main effect for light intensity [$F(4,8) = 158.51$, $p < .01$], but no interaction between noise present/absent and light intensity [$F(4,8) = 0.87$, $p = .52$].

In the 25% noise condition, there was a main effect for light intensity [$F(4,8) = 79.45$, $p < .01$] and no interaction between noise present/absent and light intensity [$F(4,8) = 1.55$, $p = .28$]. But now there was no reliable difference between the average intensity rating when noise was present (M = .00) versus absent [M = −.06; $F(1,11) = 0.07$, $p = .80$].

It is clear that in the 75% noise condition, as in the 50% condition, there is a consistent cross-modal enhancement in the brightness ratings. By contrast, there is no apparent enhancement in the 25% noise condition. The results of the meta-analyses confirm this as well.

Table 2 presents the partial correlations between the noise at trial n and the rating given at trial n, controlling for light intensity, for the 12 participants in both conditions. Employing the meta-analytic technique outlined above, we obtain 95% confidence intervals for the effect of noise of .07 to .14 in the 75% condition (z = 6.38), and of −.03 to .04 in the 25% condition (z = 0.13). As did the ANOVAs, these confidence intervals suggest a fairly straightforward

Table 1
Partial Correlations Between the Presence/Absence of Noise on Trial n and the Rating Given on Trial n, Controlling for Stimulus Intensity on n, With a 50% Presentation Probability of Noise

Participant	r	Participant	r
1	.171**	5	.114*
2	.204**	6	.144**
3	.259**	7	.131*
4	.172**	8	.171**
		9	−.006

*$p < .05$. **$p < .01$.

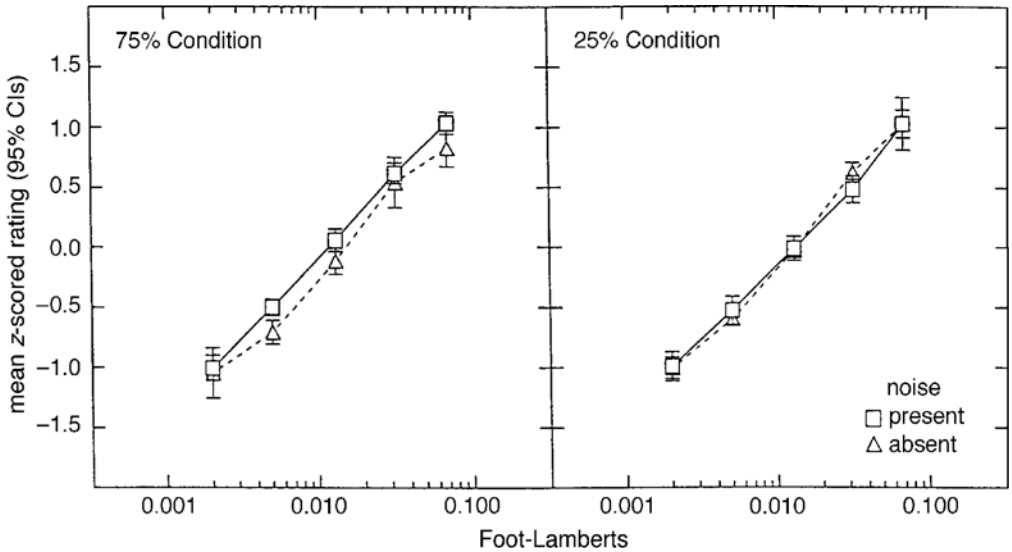

Figure 2. Mean *z*-scored ratings at each level of light intensity, with and without concurrent noise, for the 75% and 25% presentation probabilities of noise.

interpretation: There is a reliable effect of noise when it appears on 75% of the trials, but none when it appears on only 25% of the trials. An inspection of Table 2 confirms this interpretation for the 25% condition: Only 2 participants showed a reliable effect of noise, and one of these went in the "wrong" direction (meaning that the participant actually tended to rate the light as brighter when the noise was absent rather than present). The results obtained in the 75% condition, however, are somewhat more complex. As the table indicates, only 5 of the 12 participants (nos. 1, 2, 3, 9, and 12) showed reliable enhancement. Order of sessions did not matter, since 2 of the 5 participants first served at 25% probability, the other 3 first at 75% probability. It seems, therefore, that increasing the probability of concurrent noise serves to eliminate the enhancement in some people, albeit not in all.

Discussion

The results just described are broadly consistent with the hypothesis that the cross-modal enhancement of perceived visual intensity occurs as the result of a later-stage decisional process, rather than as the result of some early-stage sensory one. The results obtained in the 25% condition seem unambiguous, given that only 1 of the 12 participants showed an effect in the direction predicted by a sensory hypothesis. The results obtained in the 75% condition are somewhat less clear but intriguing. The aggregated data suggest that there is no reliable difference in the enhancement effect between the 50% and the 75% conditions. An inspection of the data on a participant-by-participant basis, however, reveals a clear difference, in that cross-modal enhancement is fairly pervasive in the 50% condition but considerably more sporadic in the 75% condition. Interestingly, this pattern of results is not strictly in keeping with most findings regarding the effect of manipulating the presentation probability of a target stimulus. Usually, increasing presentation probability leads to a small but fairly consistent shift of criterion (see Tanner et al., 1967). It is important to note, however, that the design of such prior studies differed from the design of the present study, where the concurrent burst of noise is not, strictly speaking, a component of the target stimulus.

In meta-analytic terms, there is a notable heterogeneity in the variance in the effect sizes from the 75% condition. The only potential confound from the design appears to be an order effect, which is not the case here. Unfortunately, further statistical modeling using various meta-analytic techniques is precluded without a much larger

Table 2
Partial Correlations Between the Presence/Absence of Noise on Trial *n* and the Rating Given on Trial *n*, Controlling for Stimulus Intensity on *n*, With 75% and 25% Presentation Probabilities of Noise

Participant	75% noise (r)	25% noise (r)
1	.119*	−.205**
2	.226**	−.025
3	.153**	−.021
4	.093	.023
5	−.025	.026
6	.021	−.065
7	.076	−.037
8	.038	−.021
9	.173**	.023
10	.024	.033
11	.096	.017
12	.279**	.151**

Note—The first 6 participants completed the 75% condition first; the second 6 completed the 25% condition first. *$p < .05$. **$p < .01$.

sample of effect sizes. As speculation, however, it may be worth noting that this pattern of results is consistent with a different sort of cognitive model. Consider the presentation of light plus sound and light alone in terms of the variance of the trials within a condition, which, for the binomial distribution, is ($N \times p \times q$). Were every trial to contain the noise along with the light, or were none to contain the noise, the variance would be zero. Variance is maximal in the 50% condition (equal to $.5 \times .5 = .25$) and smaller, but equal, in the 25% and 75% conditions ($.75 \times .25 = .1875$). Thus viewed, we may ask whether the variance in the presentations, so defined, is responsible for the fluctuations in the magnitude of the enhancement effect. Attentional models of perception, for instance, often suggest that the effect of a stimulus attribute on perception depends on the relative variation in that stimulus attribute, as compared with other available sources of variation (see Garner, 1974; Lutfi, 1993). Using such models as a starting point, we might expect the enhancement effect to be greatest in the 50% condition and smaller in the other two. A modification of this account, or other considerations, would still be needed to explain the difference between the results obtained in the 75% and the 25% conditions.

EXPERIMENT 2

In Experiment 2, we evaluated the effect of concurrent noise on perception of brightness in a psychophysical paradigm that avoided the use of overt ratings—namely, paired comparison. Instead of rating the brightness of a single stimulus event on each trial, as in Experiment 1, in Experiment 2 the participants received, on each trial, two successively presented visual stimuli, one of which was accompanied by the burst of noise. The task was simply to indicate whether the first or the second light appeared brighter. Of course, it would not suffice simply to present the same level of luminance twice within each trial, once with the noise and once without, since the participants might simply select the interval in which the noise was present—either because the sound actually enhanced the brightness or because the presence of the sound biased the participant to respond that way. Consequently, in Experiment 2, we varied the luminance levels of the lights presented with and without noise in a systematic fashion, according to a factorial design in which both the light plus noise and the light presented alone could take on each of five different values of luminance. Furthermore, to evaluate the effects of concurrent noise in a thorough manner, Experiment 2 tested two experimental conditions: one in which the set of luminance levels taken on by the light presented alone was identical to the set of luminance levels of light plus noise (the equal luminance, or EL, condition), and another in which the set of luminance levels taken on by the light presented alone was augmented relative to the set of luminances of the light plus noise to compensate for the difference in ratings observed in Experiment 1 (the matched rating, or MR, condition).

We included the MR condition because of the possibility that, in the EL condition, even the use of the factorial design might not overcome a tendency for participants to choose as brighter whichever interval contained the noise—especially if the participants either explicitly or implicitly assumed that, on average, the luminances of the lights presented with and without noise were equal. Thus, in the MR condition of Experiment 2, we augmented the luminances of the light presented without noise to compensate for the intersensory effect. That is, we made the ensemble of luminances of the light presented without noise slightly greater than the corresponding ensemble of luminances of the light presented with noise.

Consider predictions emanating from different hypotheses. Let us assume first, with Stein et al. (1996), that presenting a concurrent noise would actually enhance brightness. If so, then, in the EL condition, on those trials in which the luminances in the two intervals are equal, the participants should choose the interval containing the noise. Furthermore, on the remaining trials, where the luminances are unequal, the greater luminance is associated on equal proportions of trials with the light presented with and without noise. Thus, we would expect, given sensory enhancement, that on a preponderance of these trials the participants would also choose the interval containing the noise. The sensory enhancement hypothesis predicts a different result, however, in the MR condition, where the ensemble of luminances of the light presented alone is augmented to compensate for the (putative) noise-induced enhancement. Assuming an accurate assessment of the increase in luminance needed to offset the enhancement effect, on average, the participants should choose the intervals containing and not containing the noise equally.

Let us consider next the predictions emanating from a model of noise-induced response bias. In the EL condition, the hypothesis of response bias can lead to exactly the same prediction as the hypothesis of sensory enhancement: a preponderance of trials in which the participants choose the interval containing the burst of noise, depending on the success of the factorial design in suppressing the response bias. In the MR condition, the prediction could differ from that of the sensory enhancement hypothesis. If presenting concurrent noise biases response, it is possible that the small augmentation to the luminance of the light presented alone will be inconsequential, and the participants may therefore tend to judge a light accompanied by noise to be brighter than a light of slightly greater luminance not accompanied by noise. Alternatively, it is of course possible that the use of a paired-comparison method will, in fact, eliminate any response bias, leaving the responses dependent solely on luminance. Such a result would strongly support the response bias hypothesis.

Method

Participants

A total of 12 participants (2 male, 10 female) completed two 40-min sessions, as described below. All the participants were either undergraduate or graduate students at Yale University (age in years, $M = 24.00$, $SD = 4.91$). They were paid a total of $16 for their participation.

Stimuli

The stimuli used in Experiment 2 were like those in Experiment 1, with the following changes. The stimuli in the EL condition were identical to those of Experiment 1: five levels of luminance, either accompanied by a burst of noise or presented alone. For the MR condition, it was necessary to create a set of luminances for light presented alone that "matched" the ratings of brightness of light presented with noise, as observed in Experiment 1. We therefore calculated the average effect of noise from Experiment 1A in z-score units (.22) and divided this by the average effect of a 1-unit change in luminance (.49). When expressed as a ratio, the effect of noise was therefore equal to 45% of the effect of increasing luminance by one (log) step, or 0.18 log unit. Using this value, we calculated a set of five new luminance levels for the light-alone presentations in the MR condition: 2.3×10^{-3}, 5.9×10^{-3}, 1.5×10^{-2}, 3.8×10^{-2}, and 8.2×10^{-2} fL.

Procedure

The participants again first dark-adapted for 15 min with red goggles, after which we measured the visual threshold, using the same procedure as that already described. All of the participants gave thresholds (equivalent to 79% correct in 2AFC) below the lowest luminance used in the main conditions of the experiment. Therefore, the same luminance levels as those listed above were used with all the participants.

After threshold measurement, the participants returned to the booth and received instructions for the next part. They were informed that each trial would consist of the presentation of two lights in succession, separated by a brief delay, and that their task was to indicate which light, the first or the second, was brighter by pressing the "1" or the "2" on a computer keyboard. The participants were also informed that one of the two lights in each pair would be accompanied by a brief white noise burst but that they should ignore the noise when making their judgments. All the participants completed both conditions, with the order of sessions counterbalanced.

Combining each of the five possible luminances of light-plus-noise with each of the five possible luminances of light alone produces 25 possible pairs, and since each pair could have the light plus noise presented either first or second in the trial, the entire ensemble of stimulus pairs in each condition numbered 50. In each condition, the entire ensemble of 50 trials was presented in random order within a block, and the session for each condition contained seven such blocks, or 350 trials in all. The first block for all the participants in each condition was treated as practice and was discarded prior to analysis. Each trial began with a 1-sec delay, followed by a 40-msec first stimulus, a 750-msec interstimulus interval, and a 40-msec second stimulus. A 1-sec delay followed the second stimulus, after which the participant was cued to enter his or her response (without time constraint) before the next trial began.

Results

From the responses across trials for a given pair of luminances, we calculated the percentage of trials on which the participant chose the interval containing concurrent noise. The critical stimulus pairs are those falling on the main diagonal of the 5×5 stimulus matrix in each condition: the pairs in which the luminances are equal (EL condition) and the pairs in which the stimuli produced matched ratings (MR condition). Thus, we divided the trials into those on which the luminances were equal or matched (60 trials per participant in each condition) and those on which they were not (240 trials in each condition). Table 3 presents—for each participant, subset of trials, and condition—the percentage of trials on which the participant chose the light plus noise as brighter than the light alone.

An inspection of Table 3 reveals very little evidence that the concurrent presentation of the noise influenced the brightness comparisons. Recall that in the EL condition, there was a subset of five stimulus pairs (the positive diagonal of the 5×5 matrix) in which the luminances presented with and without noise were identical. On this subset of trials, the overall probability of choosing as brighter the interval containing the noise was .54, versus the .50 that would be expected by chance, an insignificant difference; furthermore, as the table indicates, only 2 of the 12 participants chose the interval with noise at a rate significantly greater than chance (binomial test). A Wilcoxon signed rank test indicated that 2 positive results out of 12 is not reliably different from what might be expected by chance ($z = -1.41$, $p = .16$). Similarly, on those trials in which the luminances differed, where again chance was .50, the participants chose the interval containing the noise on .51 of the trials, none of the 12 participants giving a proportion significantly greater than chance.

Recall that in the MR condition, the luminances of the light presented alone were increased, relative to the luminances of the light presented with noise, to compensate for the difference in ratings observed in Experiment 1A. On that subset of trials in which the brightness ratings would presumably match (the positive diagonal on the 5×5 matrix of stimulus pairs), the participants chose the interval with the noise only .37 of the time, an outcome consistent with the hypothesis that the comparisons depended on luminance alone and that concurrent presentation of the noise had no effect. This tendency to ignore the auditory signal was reliable for 8 of the 12 individual participants, which is a ratio of positive results reliably different from chance (Wilcoxon $z = -2.83$, $p < .01$). On the remainder of the trials, the interval without the noise was chosen .46 of the time, on average; statistically, a nonsignificant effect overall, and significant for only 1 of the 12 participants.

Table 3
Proportion of Intervals With Light-Plus-Noise Selected as Being More Intense Than Intervals With Light Alone When Luminance Levels Were Matched and When They Were Not, in Both the Equal Luminance and the Matched Rating Conditions

	Equal Luminance Condition		Matched Rating Condition	
Participant	$L_1 = L_2$	$L_1 \neq L_2$	$L_1 = L_2$	$L_1 \neq L_2$
1	.70**	.51	.57	.48
2	.43	.51	.27**	.44
3	.53	.51	.45	.44
4	.57	.48	.35*	.47
5	.58	.54	.38	.47
6	.52	.54	.32**	.47
7	.80**	.53	.33*	.49
8	.53	.50	.47	.45
9	.47	.51	.35*	.47
10	.43	.51	.35*	.47
11	.38	.52	.30**	.47
12	.57	.50	.30**	.43*
Average	.54	.51	.37	.46

Note—L, luminance level. $*p < .05$. $**p < .01$.

Discussion

The results of Experiment 2 reveal no evidence of cross-modal interaction. The participants, in general, showed no tendency to choose the light plus noise as brighter than light alone when the luminances were equal (EL condition) and actually chose the light alone to be brighter than the light plus noise when the luminance of the light alone was augmented slightly to compensate for the effect of noise observed in Experiment 1. These findings speak strongly against the sensory enhancement hypothesis of Stein et al. (1996) but are consistent with the hypothesis that the concurrent presentation of a burst of noise biased the participants, in the first experiment, to give slightly higher ratings to light plus noise than to light alone. The fact that participants can ignore noise, both in the case of equal luminance and in the case of luminances matched for ratings, strongly suggests a decisional source to the cross-modal enhancement of brightness ratings first reported by Stein et al.

GENERAL DISCUSSION

Brief flashes of light are rated as brighter when accompanied by simultaneous bursts of noise than when noise is absent, a phenomenon first reported by Stein et al. (1996). The goal of this study was to test explicitly two competing explanations of this cross-modal increase in brightness judgments: as an early-stage sensory enhancement or as a late-stage decisional bias. The results of the two experiments reported here speak in favor of the second explanation.

Experiment 1 showed the enhancement observed in ratings of brightness to depend strongly on the probability that the noise would accompany the flash of light. Not only would one not expect a sensory interaction to depend on the probability of co-occurrence, but also, in other domains (notably signal detection), presentation probabilities influence response criterion (Chase et al., 1983; Hansen & Well, 1984; Nachmias, 1968; Tanner et al., 1967). Furthermore, Experiment 2 showed no evidence at all of enhancement in a paired-comparison procedure, a technique known to suppress response biases.

It is notable that no enhancement was evident when the participants compared directly the brightness of light accompanied by noise and a light presented without noise. Either the decisional process underlying enhancement occurs only in tasks in which participants are called upon to make overt ratings of brightness, or, for some reason, the process is "neutralized" in a paired-comparison procedure.

In sum, there is clear evidence that concurrent presentation of noise enhances judgments of brightness, as was first reported by Stein et al. (1996), but the weight of the evidence indicates that this enhancement results from a later-stage decisional process or response bias. Next, let us briefly consider this conclusion in light of two theoretical implications.

First, the present findings are strikingly consistent with decisional models (e.g., Ben-Artzi & Marks, 1995a) that have been offered to explain other cross-modal interactions involving relatively simple sensory dimensions, such as loudness and brightness. In particular, cross-modal interactions have commonly been observed in studies that have adopted the selective-attention paradigm championed by Garner (1974). In Garner's paradigm, participants attempt to classify stimuli as quickly as possible according to the values on one (criterial) dimension while values on another (irrelevant) dimension vary orthogonally. In the cross-modal version of Garner's paradigm, the criterial dimension belongs to stimuli in one modality, whereas the irrelevant dimension belongs to stimuli in another.

In one of the experiments reported by Marks (1987), participants classified visual stimuli according to their brightness while the loudness of a concomitant auditory stimulus varied in an unpredictable way from trial to trial. Although the loudness of the irrelevant sound was uninformative, it nevertheless affected the speed (and the accuracy) of visual classification. Responses were quicker (and more accurate) when the lights and the tones were congruent (e.g., soft tone accompanying dim light, loud sound accompanying bright light) than when they were incongruent (soft + bright, dim + loud). Furthermore, random variation in the brightness of an irrelevant light modified, in a similar fashion, the speed and accuracy with which participants classified tones according to their loudness.

Congruence interactions like those just described pervade measurements of cross-modal selective attention, turning up not only in studies of loudness and brightness (Marks, 1987), but also in studies of pitch and brightness or lightness (Marks, 1987; Martino & Marks, 1999; Melara, 1989), pitch and vertical spatial position (Ben-Artzi & Marks, 1995b; Bernstein & Edelstein, 1971; Melara & O'Brien, 1987), pitch and visual shape (Marks, 1987), and vibrotactile pitch and visual lightness (Martino & Marks, 2000). To account for these interactions, Ben-Artzi and Marks (1995a) proposed a decisional model: According to this model, information that accrues from an irrelevant stimulus will, if its value is congruent or incongruent with the values of the relevant stimuli, produce shifts in the observer's criteria for responding to the relevant stimuli. That is, when a person classifies lights as dim or bright, a soft tone is congruent with dim and incongruent with bright and, therefore, will "bias" the responses, lowering the person's criterion for classifying the visual stimulus as dim and raising the criterion for classifying it as bright. A loud tone will produce comparable shifts in criteria in the opposite direction. The present findings are consistent with the model of Ben-Artzi and Marks (1995a), with the reasonable proviso, in speeded-classification tasks, that the magnitude of the shift in response criteria increases when the magnitude of the irrelevant stimulus increases.

A second theoretical implication pertains to mechanisms of decision and judgment in psychophysical rating paradigms. It is worth noting another approach that has been employed to dissociate decisional from sensory contributions to cross-modal enhancement and to which cross-modal enhancement may, therefore, be relevant—

namely, the analysis of sequential effects in judgment. A substantial literature has treated the way in which responses given on trials depend on prior stimuli and responses; a particular goal has been to distinguish decisional and sensory contributions to these sequential effects (e.g., DeCarlo & Cross, 1990; Jesteadt, Luce, & Green, 1977; Macdonald, 1976; Staddon, King, & Lockhead, 1980; Tanner et al., 1967; Ward, 1979, 1982, 1990).

The study of sequential processes has led to descriptions of two commonly described effects: assimilation and contrast. Assimilation has been modeled as the positive correlation between the judgment on the previous trial, $n-1$, and the judgment on the current trial, n, and has generally been explained as the outcome of a decisional process. Contrast, on the other hand, has commonly been modeled as a negative correlation between the physical intensity of the stimulus on trial $n-1$ and the judgment on trial n and has been identified as sensory in origin (Ward, 1979, 1982). Unfortunately, analysis of sequential effects depends strongly on one's theoretical model. Disagreements exist over such critically important issues as the number of preceding trials that produce sequential effects, whether the relations between variables are linear, and the direction (positive or negative) of the contrast effect. To these theoretical issues, we now add the question of whether, or how, cross-modal interactions, such as the one studied here, may in turn interact with sequential effects. Such considerations are best left to future studies designed specifically to determine the possible contribution of cross-modal interactions to sequential effects. It is plausible, for instance, that cross-modal enhancement, being decisional rather than sensory in origin, will affect those sequential processes that tap most strongly into decisional, as opposed to sensory, mechanisms.

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